

Polarization diversity for Brillouin distributed fiber sensors based on a double orthogonal pump

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ABSTRACT

We demonstrate a novel Brillouin optical time domain analysis sensor deploying a polarization diversity technique which eliminates the need for polarization scrambling, providing measurements that are largely immune to the state of polarization of the probe wave and the pump pulses throughout the sensing fiber. This can be exploited to reduce the measurement time or can lead to an enhanced precision. Proof of concept experiments demonstrate a 651 Hz sampling rate with 1m resolution over a 930m sensing fiber.

Keywords: Brillouin distributed sensors, Brillouin optical time domain analysis (BOTDA), Dynamic BOTDA.

1. INTRODUCTION

Brillouin optical time domain analysis (BOTDA) sensors are becoming increasingly attractive for a wide set of applications, owing to their capability to provide high precision distributed measurements of the strain or temperature profile in extremely large structures. Nevertheless, BOTDA sensors have been traditionally limited to static measurements, mainly due to the need for scanning the Brillouin spectrum. However, dynamic variations of temperature or strain can be measured by modifying the sensor technique. This can be made by tuning the probe wave to the skirt of the Brillouin gain spectrum so that variations in BFS are translated to changes in the amplitude of the detected probe wave¹. A key challenge faced by dynamic BOTDA sensors is to reduce the extra time added to the measurement due to the need to compensate for the polarization dependence of Brillouin interaction. This polarization dependence is usually overcome by performing a time-domain polarization scrambling of the probe wave or of the pump pulses. However, this forces a larger number of averages in the measurement, as a significant number of states of polarization (SOP) must be averaged in order to obtain a polarization independent measurement. Another possibility is to use a polarization switch, so that two orthogonal SOPs are sequentially launched into the fiber, limiting the measurement time to that of the switching time of that device². A third approach is to implement a passive polarization scrambler using an unbalanced Mach-Zehnder interferometer³. This provides an excellent polarization scrambling with no time penalty in the measurement, but it's limited to sensor setups deploying single wavelength CW probe signals.

Recently, we proposed a dynamic BOTDA sensor based on a phase-modulated probe wave and self-heterodyne detection. This technique enhances the SNR in relation to the conventional direct detection scheme and is able of performing measurements largely immune to attenuation in the optical fiber⁴. In this paper, we propose an improved setup based on the use of a double orthogonal pulsed pump, which retains the advantages of the previous technique and adds a new one: the capability to perform polarization independent measurements. Furthermore, the novel polarization diversity technique needs of virtually no manual polarization control, so that it may be suitable for practical sensor implementations.

2. FUNDAMENTALS

Figure 1 schematically depicts the fundamentals of the proposed system. A single tone phase-modulated probe wave is injected in one end of the optical fiber under test, while two orthogonal pump pulses are introduced at the other end. This probe wave interacts with the pump pulse along the fiber via stimulated Brillouin scattering (SBS) and is directed to the receiver using a circulator. Finally, the detected RF electrical signal is demodulated in a synchronous demodulator⁴.

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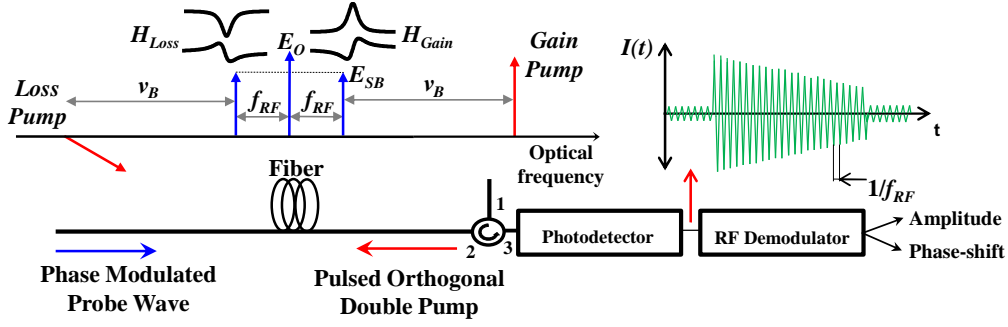


Figure 1. Schematic representation of the double orthogonal pump SBS interaction and the received signal.

As schematically shown in Fig. 1, the wavelengths of the pump pulses are adjusted so that each of the two orthogonal pumps interacts with one of the modulation sidebands of the phase-modulated probe wave. The aim of this double interaction is to produce a Brillouin gain over one of the sidebands, while a Brillouin loss is generated over the second one. If the modulation frequency of the probe wave is much higher than the Brillouin bandwidth, we can consider that each SBS interaction only affects one sideband of the modulation, leaving the other sideband and the carrier unaffected. Then, the optical field at the input of the photodetector coming from the interaction of pump and probe at a particular location in the fiber, z , is given by the following expression:

$$E(t) = E_0 \exp(j2\pi\nu_0 t) + E_{SB} \exp(j2\pi(\nu_0 + f_{RF})t) H_{Gain}(\nu_0 + f_{RF}, z) - E_{SB} \exp(j2\pi(\nu_0 - f_{RF})t) H_{Loss}(\nu_0 - f_{RF}, z) \quad (1)$$

where E_0 and E_{SB} are the amplitudes of the optical fields of the carrier and first sidebands of the phase-modulated probe wave (higher-order sidebands were neglected, assuming a small modulation index), ν_0 is the optical frequency of the carrier, f_{RF} is the modulation frequency and H_{Gain} and H_{Loss} are, respectively, the complex Brillouin gain and loss spectra at position z , which can be described by:

$$H_{Gain}(\nu, z) = \exp(\eta_G (G_{Gain} + j\phi_{Gain})) \approx 1 + \eta_G (G_{Gain} + j\phi_{Gain}) \quad (2)$$

$$H_{Loss}(\nu, z) = \exp(\eta_L (G_{Loss} + j\phi_{Loss})) \approx 1 + \eta_L (G_{Loss} + j\phi_{Loss}) \quad (3)$$

where G_{Gain} and G_{Loss} are the Brillouin gain factors, and ϕ_{Gain} and ϕ_{Loss} the phase-shifts of each Brillouin interaction. The approximation in the second term of Eq.(2) and Eq.(3) is obtained assuming a small gain (or loss), which is the case for BOTDA sensors. The polarization dependence of SBS interaction is mathematically modeled by the real factors η_G and η_L which determine the mixing efficiency of the counterpropagating signals. In general, this factor η ($0 \leq \eta \leq 1$) can be described as a function of the SOP of probe and pump signals.

As depicted in Fig. 1, the symmetry of both Brillouin interactions is so, that the phase-shift induced over both sidebands will be equal ($\phi_{SBS} = \phi_{Gain} = \phi_{Loss}$), and the gain will be of identical magnitude but opposite sign ($G_{SBS} = G_{Gain} = -G_{Loss}$). In that case, the resultant RF signal after detection of the optical field in Eq. (1) can be described in phasorial form as:

$$I|_{f_{RF}} = E_0 E_{SB} (\eta_G + \eta_L) (G_{SBS} + j\phi_{SBS}) \quad (4)$$

If we now consider that both sidebands of the phase-modulated probe wave have the same SOP, it is easy to prove that η_G and η_L will be complementary⁵:

$$\eta_G + \eta_L = 1 \quad (5)$$

Notice that if we update Eq. (4) considering this last result, the detected power shows no dependence on the SOP of the optical beams involved in SBS interaction. Therefore, the technique removes the need for polarization scrambling, as Brillouin interaction will be produced over the entire length of fiber. This can be understood intuitively considering that for any given location of the fiber both Brillouin interactions remain complementary, so that their sum is always equal to a single Brillouin interaction with aligned SOP for probe and pump waves.

Furthermore, the detected RF phase-shift is independent of the particular Brillouin gain peak experienced by the probe wave and of the received optical power, which is a key feature for dynamic measurements⁴. Therefore, the same technique described in⁴ can be deployed to perform dynamic BOTDA measurements.

3. EXPERIMENTS

The experimental setup shown in Fig. 2 was assembled in order to demonstrate the system. The output of a 1551.4 nm laser source is divided in two optical branches with an optical coupler. In the upper branch, the optical beam is pulsed using a semiconductor optical amplifier (SOA). This pulsed beam is directed to a Mach-Zehnder electrooptic modulator (MZ-EOM) driven by a microwave signal of 9.6 GHz and biased in minimum transmission, so that two pulsed sidebands are generated, while the optical carrier is suppressed.

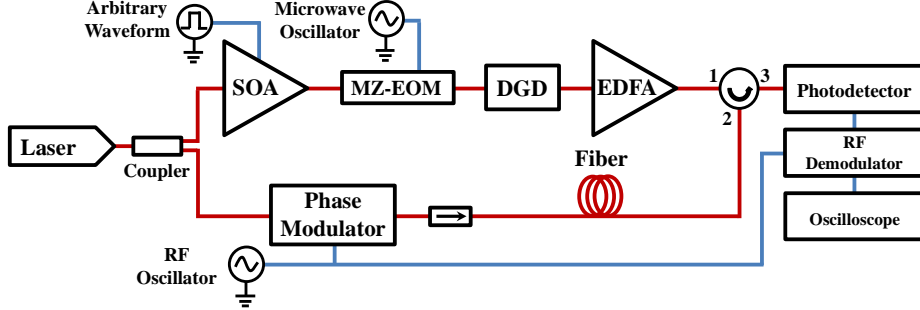


Figure 2. Experimental setup for the polarization diversity BOTDA sensor based on a phase-modulated probe wave.

A differential group delay (DGD) module, which provides a group delay between two linear orthogonal polarization states, is used to orthogonalize the SOP of the two sidebands of the optical double sideband with suppressed carrier (ODSB-SC) modulation⁴. In order to do this, the light is launched into the birefringent material, where the phase-shift between two wavelengths spaced a certain frequency Δf when they travel through the birefringent material is given by:

$$\Delta\theta = 2\pi \cdot \Delta f \cdot \Delta\tau \quad (4)$$

where $\Delta\tau$ is the differential group delay induced by birefringence. Therefore, depending on the wavelength of the incident beam, the birefringent material provides different polarization states at its output. As a result, in order to obtain linear orthogonal polarizations between both sidebands of the ODSB-SC modulation, the polarization state of the amplitude modulated signal has to be linear at 45° with the material axis of the DGD module. In our experiment, a DGD module with $\Delta\tau=26\text{ps}$ was deployed, so that the two pulsed sidebands of the modulation, separated by 19.2 GHz, were made orthogonal. Then, they are amplified in an erbium doped fiber amplifier (EDFA), and the resulting pump pulses are directed via a circulator to a 930m-long fiber.

In the lower branch, the probe wave is generated with an electro-optic phase modulator driven by a 1.3 GHz RF signal. The modulation frequency is chosen so that the upper sideband of this modulation interacts via SBS with the lower sideband of the ODSB-SC modulated pump pulse, while the lower sideband of the phase modulation is affected by the higher frequency pump pulse. The BOTDA trace captured in the oscilloscope is depicted in Fig.3 (a), showing negligible polarization dependence, as compared with a conventional BOTDA trace (Fig.3 (b)). The trace in Fig.3 (b) was obtained by removing the DGD module from the setup. Both traces have been acquired using a 128 averaging rate, but deploying no further technique to compensate the polarization dependence of SBS interaction.

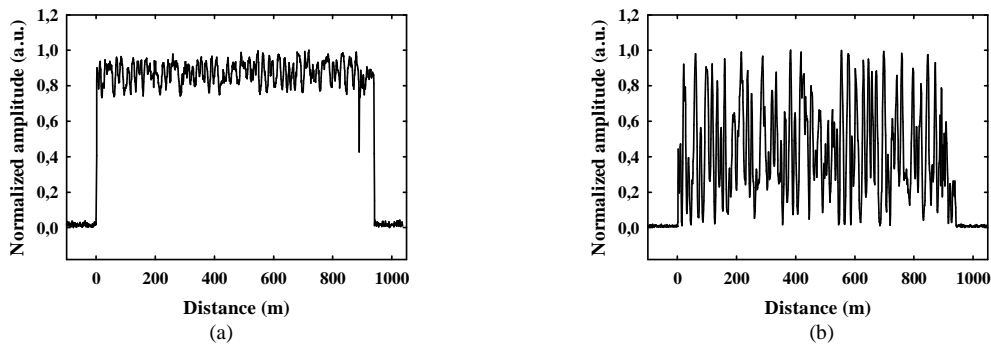


Figure 3. Measured BOTDA trace (a) when the polarization diversity technique is implemented and (b) when the DGD module is removed from the setup.

Finally, a 1-meter section at the end of the 930-m fiber was affixed by epoxy resin onto the surface of a 1 m cantilever beam. The cantilever beam was made to vibrate so that dynamic distributed measurements of the induced strain along the fiber could be performed. The pulse duration was set to 10 ns to obtain 1-m spatial resolution. Moreover, a BOTDA trace was captured every 12 μ s and 128 averages were used. Therefore, the short term sampling rate of our measurements was 651 Hz. However, the limitations of the available acquisition instrumentation did not allow sustaining that rate for longer measurements, resulting in an effective 120 Hz measurement rate for this experiment. Fig. 4 shows the measured strain in the final locations of the fiber when the cantilever beam is made to vibrate. The distributed measurement is also demonstrated, as only the section of the fiber attached to the cantilever beam is suffering strain, while the adjacent sections of fiber remain steady.

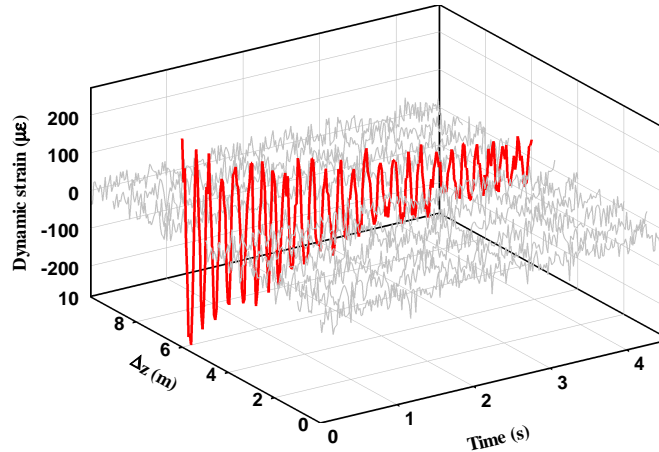


Figure 4. Fast-acquisition polarization-compensated measurement of the strain induced at the last locations of the fiber (grey traces), where the cantilever beam (red trace) is made to vibrate.

4. CONCLUSIONS

A dynamic Brillouin distributed sensor featuring a novel polarization diversity technique has been proposed and demonstrated. The sensor relies on the RF phase-shift spectrum, which was shown to be largely immune to variations of the Brillouin peak gain, attenuation on the fiber, or changes in the power of the pump pulses. The polarization diversity technique removes the need for polarization scrambling or for any other polarization compensating technique, so that the measurement time can be greatly reduced. The capabilities of this novel scheme have been demonstrated, performing a fast dynamic distributed strain measurement in a cantilever beam with high measurement range and precision.

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